Operations and Autonomy for the Mars Pathfinder Microrover

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Outline

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Microrover Flight Experiment (MFEX) Mission Objectives

- **Meet cost, mass, and schedule requirements**
- **Minimize rover impact on Pathfinder project cost and risk**
- **Survive launch, cruise, landing**
- **Perform surface operations**
  - complete technology experiments
  - carry out APXS rock and soil measurements
  - image lander
- **Operating range:**
  - operate primarily within 10 meters of lander
  - drive up to 100 meters on the Martian surface
  - be capable of operating beyond the lander's horizon
- **Lifetime:**
  - complete 7-sol primary mission
  - be capable of extended mission up to 30 sols duration

Microrover Flight Experiment (MFEX) Mission Objectives

- All cost, mass, and schedule requirements have been met. The MFEX budget, including design, development, implementation, and operations, is $25M. The mass allocation for the rover and its lander-mounted support equipment (tie-downs, rails, ramps, and UHF radio link) was 16 kilograms, while the actual combined mass of all rover elements is 15.2 kilograms.

- The interfaces between rover and lander were simplified as much as possible to reduce dependencies between the two developments. For example, there is no electrical interface between the rover and the lander. To wake up the rover during pre-launch and cruise mission phases, a reed relay switch in the rover is activated by a magnetic coil mounted on the lander petal; activation of the switch allows the rover's own batteries to power its bus. For telemetry processing, the rover transmits already formatted packets to the lander, which then processes them in the same manner as packets generated by the lander itself.

- Rover mission success is determined largely by the accomplishment of the surface operations objectives. One complete set of technology experiments, including soil mechanics, material adherence, and wheel abrasion, together with one APXS rock data collection, and an image of the lander to assess its post-landing condition, have been defined to constitute 90% of mission success. The remaining 10% can be achieved by completing additional sets of technology, APXS, and imaging activities.

- Operating range: The rover is expected to operate primarily within 10 meters of the lander; this is considered the effective limit of usefulness of the lander stereo images for directing the rover and identifying sites of scientific interest. If desirable destinations for the rover are identified further from the lander (in particular during the extended mission), then the rover may be commanded to travel as far as the lander's horizon. The rover's design allows it to drive several hundred meters from the lander before passing out of communications range. The software design will enable it to respond to communications loss in one of two specified ways: 1) stop and back up to re-establish communication, or 2) continue executing its sequence, which will bring the rover back into communications before it completes. While this long distance driving is feasible due to the rover's architecture, the rover's hardware is only required to support 100 meters of traverse on the Martian surface.

- Lifetime: The rover's prime mission has been designed to allow the rover to accomplish its surface operations objectives (above) in the first seven sols of operations. In addition, no element of the rover's design should preclude its operation for a full 30 sol extended mission, during which greater risks may be taken. The only exhaustible resource (other than normal wear) is the non-rechargeable battery; the rover is capable of performing its entire mission, with the exception of night time APXS data collection, even if the batteries are unavailable after landing.

Derived Rover Functional Requirements

To meet its mission objectives, the MFEX rover must be able to:

- Communicate with lander to request commands and downlink telemetry
- Wakeup in response to either lander or on-board triggering
- Execute command sequences
- Unstow itself and drive down the lander ramps
- Traverse the surface of Mars while detecting and avoiding hazards
- Reach targets of interest as designated by Earth-based operators
- Maintain knowledge of its internal state
- Operate on-board experiments, including the APXS, MAE, and WAE
- Manage its limited available power
- Maintain its internal temperature within acceptable limits
- Perform a useful contingency mission if communications is lost
- Recover from command execution failures
- Continue to operate in the event of hardware degradation

Rover Technical Description

- **Mass: 10.5 kilograms**
- **Volume**
  - Stowed: 75cm (l) by 48cm (w) by 19cm (h).
  - Deployed: 65cm (l) by 48cm (w) by 30cm (h).
- **15W peak solar power available, with primary battery for backup and night operations (i.e., APXS data collection)**
- **Rocker-bogie mobility chassis with 6-wheel drive, 4-wheel steering, capable of traversing hazards 1.5 wheel diameters height**
- **Processor: Intel 80C85, 2Mhz, 100Kips**
- **Navigation Sensors:**
  - Forward stereo monochrome cameras with laser light stripers
  - Accelerometers, rate sensor, odometry and articulation sensors
- **Onboard experiments:**
  - Material Adherence Experiment (MAE)
  - Wheel Abrasion Experiment (WAE)
  - Alpha Proton X-ray Spectrometer (APXS) with deployment mechanism
  - Other experiments rely on rover navigation sensors and imaging sensors

Rover Technical Description

- GaAs solar panel powered (15W peak); primary battery backup (30W available)
- 6-wheel drive, 4-wheel steerable, rocker-bogie mobility chassis (17cm clearance)
- Speed: 0.4 m/minute in nominal terrain
- Pop-up UHF antenna at solar panel edge for communication w/lander (9.6Kbaud, 2Kbps@500m)
- LeRC material adherence experiment (MAE) on solar panel (measure panel output)
- LeRC wheel abrasion experiment (WAE) on center wheel/bogie
- Electronics/batteries in warm electronics box (WEB)
  - temperature ±40°C (flight allowable)
  - WEB constructed of epoxy sheet/spar solid silica aerogel (20mg/cc) insulation
  - daytime heat from solar panels plus 3 RHU's
  - no night electric heat utilized (less than 2W heat leak)
- APXS sensor & deployment mechanism mounted on rear
- Hazard range detection system mounted on front
  - CCD lines/light stripers (detect hazards to 1 vehicle length (65cm))
- Stereo front cameras (768 x 484 pixels; 4mm, wide-angle lens; FOV 127° x 94°; 3 mrad/pixel. Each camera is mounted about 25cm above the terrain surface)
- Mono/color rear camera for terrain, wheel/track and APXS target imaging
- Single CPU (Intel 80C85, 2Mhz, 100Kips) and discrete component boards (class B/mil spec/commercial parts). 4 types of memory : 16Kbyte PROM, 64Kbyte rad hard RAM, 176Kbyte EEPROM, 512Kbyte RAM, addressable in 16Kbyte pages. Two double-sided boards implement all processing and power conditioning/distribution.
- Round robin clocking of sensors (78 sensors, 11 actuators, 65 switches)
- On-board data compression (4.9:1 for images) & packetizing; "bent-pipe" informational interface to lander
- Mass: 10.5 kilograms
- Stowed volume: 75cm (l) by 48cm (w) by 19cm (h).
- Deployed volume: 65cm (l) by 48cm (w) by 30cm (h). Deployed antenna is 30cm.

Rover Surface Operations Scenario

- **Rover operations team prepares one command sequence each Martian sol**

- **One uplink opportunity per sol**

- **Up to three telemetry downlink periods per sol**

- **Rover nominally operates autonomously for one sol (>24 hours) until receipt of next command sequence. Activities during a sol include:**
  - Imaging
  - Traverse to designated sites of interest
  - Multiple technology experiments
  - APXS sensor placement & instrument operation (day/night)

- **Lander camera captures stereo image of rover at its end-of-day location**

- **Downlinked images and rover telemetry used by rover team to assess rover state and plan next sol's activities**

Rover Surface Operations Scenario

- The rover operations team prepares one command sequence per sol (one Martian day). The design of each sequence is based on a combination of 1) the rover state assessment provided the by the Rover Engineering Analysis Team, 2) the science and technology experiment requests from the Experiment Operations Team, and 3) the feasibility of the requested operations given the trafficability of the Martian terrain and the safety of the vehicle. The uplink team designs a sequence to fulfill as many of the science and technology requests as possible while maintaining the health of the rover.

- On a given sol, there is usually only one opportunity to uplink rover and lander command sequences. This opportunity corresponds to early morning of the Martian day.

- Telemetry will be downlinked during up to three periods per sol. The first downlink occurs just prior to the morning uplink. The mission operations team has a short time to review the telemetry to determine whether any contingencies have occurred during the Martian night that would preclude uplinking the nominal sequence. The second downlink is around mid-day, before the rover has completed its primary operations for the sol. The final downlink takes place mid- to late-afternoon on Mars, and provides the primary telemetry necessary to plan the rover's next sol's activities.

- The rover nominally operates autonomously for one sol (>24 hours) until receipt of the next command sequence. During a typical sol, the rover will complete an APXS data collection that was carried out during the prior night; capture a rear color image of the APXS site; traverse to an appropriate site and perform a series of soil mechanics experiments, including several subframe images of soil mounds and depressions created by running individual wheel motors; perform a WAE experiment and several MAE experiments; traverse to a designated rock or soil location; place the APXS sensor head; capture end-of-day operations images with its forward cameras; begin APXS data collection; and shut down for the night. APXS data collection usually occurs overnight while the rover is shutdown.

- Once the rover has completed its traverse activities for the sol (usually by 2:00pm Mars local time), the Lander camera captures one or more stereo images of the rover at its end-of-day location. These images are required for operations, and are therefore placed in a high priority queue to ensure that they are downlinked during the current sol.

- Downlinked images and rover telemetry are used by the rover team to assess the rover's state and plan the next sol's activities. The uplink team uses the lander images of the rover to localize and update the rover's location on the Martian surface, in order to prevent the accumulation of dead reckoning error from sol to sol. These images of the rover are merged with the stereo panorama of the terrain which is built up over the first few sols of operation. Rover destinations are then designated in the stereo display of the Rover Control Workstation, and integrated with the rest of the rover command sequence.

Command Sequence Generation

- **Command sequence defines rover activities for one sol, plus "runout" in event next sequence is delayed. Command sequences contain:**
  - Parameter changes for "housekeeping" functions
  - Update of rover's position and orientation
  - Traverse commands ("Go to Waypoint") specifying destination and intermediate waypoints avoiding obvious hazards
  - Lower level motion commands (e.g., "Move", "Run Motor") for terminal positioning
  - Sequence fragments defining experiment execution

- **Sequences designed by human operators using custom Rover Control Workstation (RCW). Features of RCW include:**
  - Graphical user interface for building rover command sequences and trafficability assessment
  - Integrated stereo display and graphics overlays for designation of rover navigation waypoints
  - Constraint checking to prevent input of out-of-range values

- **Primary telemetry inputs to RCW for traverse planning are calibrated lander stereo images of traverse area and current rover location**

- **RCW generates rover command sequence files in format compatible with Mars Pathfinder project uplink tools**

Command Sequence Generation

- Typically, one command sequence defines the rover activities for one sol (including both day and night operations), plus "runout" commands in the event the next sequence is delayed. Traverse commands are only a small fraction of most command sequences. Other commands (or sets of commands) control the following functions: update of rover position and orientation; imaging; passing of commands to the APXS instrument; collection of soil mechanics, MAE, and WAE experiment data; operation of individual actuators; parameter settings for "housekeeping" functions such as heating times and self-diagnostic health check rates; rover shutdowns with appropriate wakeup times; error masking and clearing; contact sensor masking; low-level activation of devices and actuators (if needed); telemetry buffering options; enabling of battery usage for various devices.

- Unlike previous planetary exploration missions, we must generate new command sequences within a few hours based on telemetry downlinked daily. We cannot decide where the rover should go next, or what it should do in the process, until we receive end-of-day images and engineering data showing us where the rover has actually gone, and what is its current state. To facilitate this rapid command turnaround, we are generating a set of command sequence macros for activities that the rover performs on a repetitive basis. These macros encompass experiment operations, APXS site imaging, final approach to rocks of different sizes, night time APXS data readouts, and common groupings of parameter settings.

- Human operators design rover command sequences at the Rover Control Workstation (RCW). The operator can "fly" a 3-D rover icon through the stereoscopic display of the Martian terrain. By inspecting the stereo scene, as well as placing the rover icon in various positions within the scene, the operator can assess the trafficability of the terrain. By placing the icon in the appropriate position and orientation directly over the stereo image of the actual rover on the surface, the rover's location and heading are automatically computed; when this information is uplinked to the rover, accumulated dead reckoning error is corrected. The rover driver specifies the rover's destinations by designating a series of waypoints in the scene, generating waypoint traverse commands. Other types of commands are inserted into the sequence using a customized graphical user interface.

- Since downlink communications bits are a scarce resource, the telemetry volume produced by a given sequence must be estimated during sequence review to ensure that the rover does not exceed its allocation for the sol.

- The RCW generates rover command sequence files in a format compatible with the Mars Pathfinder project uplink tools. These files are delivered to the project flight engineers, who insert them into the sequence load for the spacecraft. Once uplinked to the lander, the rover sequence is activated, placing it in the lander's rover buffer, to be provided to the rover the next time the rover requests a command sequence.

Rover Autonomy

Rover autonomous capabilities are focused in these principal areas:

- **Autonomous navigation through natural terrain**

  Due to communications constraints (light time delay, limited bandwidth, infrequent opportunities) and the need to respond in real-time to uncertain terrain conditions, the rover must be capable of autonomous navigation. Navigation capabilities include:
  - Traverse to designated coordinates
  - Terrain hazard detection and avoidance
  - Rock finding for APXS sensor head placement

- **Response to contingencies**
  - Command loss
  - Component failures

- **Resource management**
  - Thermal control
  - Power management

Rover Autonomy

The rover has autonomous capabilities in the areas of terrain traverse, contingency response, and resource management.

- The rover will autonomously navigate through the natural terrain of the Martian surface. The time-delay (10 minutes one way on July 4) intrinsic to communications between Earth and Mars precludes real-time human operator control of the rover. Continuous communications between Earth and Mars is not feasible in any case, due to Deep Space Network (DSN) contention issues. In addition, Earth-based operators viewing lander-based images of the scene may not be able to discern all hazards to the rover. Therefore, the rover must be able to respond to sensor input (from accelerometers, rate sensor, encoders, articulation sensors, and the proximity hazard detector) on its own in real time in order to reach sites of interest in reasonable time, as well as to protect itself from attempting hazardous, potentially mission-ending maneuvers.

- Communications to the rover can potentially fail across two links: the lander receiver may fail, preventing rover sequences from being uploaded; and the local UHF link between the lander and rover may become inoperative. In the first case, the rover operates normally, because the lander will periodically activate pre-loaded backup rover sequences. In the second case, the rover will eventually trigger its own on-board contingency sequence, and perform a generic mission, transmitting its telemetry without handshaking in the hope that the lander is still listening. (The rover's actions in these two situations is described more fully below in "Contingency Scenario Responses".)

- The rover can autonomously recognize device failures, and in some cases compensate for those failures. The "faster, better, cheaper" approach to spacecraft design has required an acceptance of higher risk, with few fully redundant components. Each time the rover performs an internal health check, it will increment a "failure counter" for each apparently failed device; once the failure count is high enough, no attempt will be made to rely on that device during command execution. If the device begins operating again, the failure count will decrement.

  Some fall-back approaches to device failures are used. If the rate sensor fails, turn angles will be estimated by time instead. If potentiometers or encoders cease to operate, time-based steering or driving can be used.

- Rover resource management is similar to that performed by other spacecraft. The rover monitors its internal temperatures on a regular basis between command executions, turning its heaters on or off as necessary. The intent of the thermal control function is to maintain the WEB temperature between -40°C and +40°C throughout the rover mission. This is accomplished by heating the WEB to nearly 40°C by the end of the sol's daytime activities; once the rover shuts down, the WEB will cool through the Martian night, bringing its internal temperature down to approximately -25° C by the time the rover resumes operation the next morning.

  The rover also determines the solar power available at a given time, and assesses whether there is sufficient power to execute the next command. By command, battery usage for certain devices can be enabled.

Rover Navigation

- **Waypoint Traverse**
  - Rover traverses to waypoints specified by human operator (2-3 m/sol)
  - Capability to reach desired target dependent on accurate designation of waypoints in lander stereo images
  - Rover deviates from straight-line path between waypoints in response to detected hazards (i.e., rocks, drop-offs, excessive tilt, unsafe vehicle articulation)
  - Reflex-based control has no memory; no true onboard path planning
  - Rate sensor and odometry support dead reckoning
  - Daily updates of rover position/orientation provided from the ground based on analysis of lander stereo images, minimizing error accumulation

- **Laser hazard detection system detects rocks, drop-offs, and slopes**
  - Rover stops, captures image with selected lasers active
  - Given "flat-earth" assumption, laser stripe will be visible in known position on CCD scanline
  - Hazards cause laser stripe to slide along scanline (e.g., rock) or disappear (drop-off)
  - Repeating process with 5 lasers generates sparse "map" of ground in front of rover (4 x 5 grid of elevation points)
  - Hazard thresholds are empirically determined
  - Not a stereo imaging system, but does estimate object heights

Rover Navigation

- The "Go to Waypoint" command is the primary implementation of autonomous rover navigation. The rover operates in a coordinate frame that becomes fixed to the surface of Mars at the time the lander completes sun-finding and identifies Martian north. (The origin of the frame is nominally at the center of the base of the lander.) The human operator specifies the x,y coordinate of a site of interest (e.g., a rock APXS target) in this frame; in addition, the operator specifies the maximum time the rover may take to execute the traverse to this location before the command times out. Intermediate waypoints are also be defined if there is a preferential path toward the final destination (i.e., obvious hazards to be avoided). If the rover is not already facing the next waypoint, it will drive in an arcing turn toward the goal, until it is facing destination. It will then drive an approximate straight line, adjusting its path when it detects drift off its course.

  The rover can identify several types of hazards. They include proximity-detected rocks, drop-offs, and slopes; excessive tilt of the vehicle; triggered contact sensor; loss of communications; motor stall; and the lander as a virtual hazard. The specific hazards that the rover is allowed to avoid autonomously (without aborting the traverse) are specified by a settable parameter. (Most conservatively, only autonomous avoidance of proximity hazards is enabled. However, in rough terrain, contact sensor recovery is also commonly enabled.) If the rover detects a proximity hazard, the vehicle turns in place in increments, until the hazard is no longer detectable. Then the vehicle drives forward one-half vehicle length, after which it resumes normal traverse operations, heading back towards the goal location. At this point, the rover has no memory of the hazard that it has just avoided; it does not maintain a permanent map of the terrain through which it traverses.

  The rover is expected to traverse about 2 to 3 meters per sol. The success of a traverse is dependent on the daily update of the rover's position and orientation using the end-of-day lander images, as well as accurate designation of desired destinations by the Earth-based operators. The rover cannot reach a desired destination unless it is provided with both an accurate indication of where it is (including where it is pointing) and where to find its destination.

- Proximity hazard detection is performed using the forward cameras and five laser stripers. Every seven centimeters of traverse, the rover stops and executes a sensing cycle. The rover captures an image both with and without a laser active. Selected scanlines from each image are differenced to locate the laser spot in the scene. If the terrain is flat and level, the laser spot with be visible in a known position along the scanline. Deviations from flat and level ground will cause the laser spot to slide along the scanline, indicating a rock or depression. If the spot cannot be found in the difference image, a significant drop-off may exist. Repeating this process for 5 lasers and four sets of scanlines per difference image generates a set of 20 terrain height measurements. Height differences between adjacent measurements can indicate a rock or hole; sufficient height difference between the lowest and highest measurements in the set indicates a steep slope. False hazard detections can occur if the camera view of a laser spot is blocked by a craggy surface, so ignoring single instances of data drop-outs is possible by modifying parameter settings in appropriate terrains.

Rover Navigation (cont.)

- **Navigation safety features:**
  - Heartbeat: the rover stops periodically and confirms contact with lander before continuing traverse; if communications fails, rover retreats short distance and attempts to reestablish contact
  - Lander avoidance: origin of navigation coordinate frame (lander position) is treated as a hazard, and avoided if necessary
  - Bumper contact sensors: Any obstacle which somehow eluded the laser hazard detection system will, in the worst case, trigger the bumper contact sensors, aborting the traverse or initiating avoidance response
  - If waypoint destination is not reached within specified allotted time, the command will time out, aborting the remaining traverse
- **"Find Rock" command:**
  - If the rover identifies a rock hazard during its traverse, it will stop, then turn in place while using its hazard detection sensors to determine the extent of the object, then turn to face the center of the rock.
  - Used to fine position the rover for APXS data collection
- **Other traverse capabilities:**
  - Move and Turn commands drive the rover without active hazard detection

Rover Navigation (cont.)

- We have implemented several navigation safety features to protect the rover during waypoint traverses:

  To ensure that the rover does not inadvertently traverse beyond communications range, it stops periodically (about once per vehicle length of traverse) to perform a “heartbeat” communications test. If the lander responds, the rover resumes its traverse. Otherwise, the rover retreats 30 cm, turns 45 degrees, and attempts to reestablish contact with the lander.

  The lander itself is a potentially serious hazard to the rover. Cleats on the rover’s wheels can catch airbag material, possibly permanently entangling the vehicle. A settable parameter permits operators to specify just how close to the lander the rover is allowed to go. This virtual hazard is triggered only if the rover is within the hazard radius and driving towards the lander. If the rover is inside the danger zone, but driving away from the lander, it will perceive no hazard. Again, depending on parameter settings, the rover will either autonomously avoid the lander, or abort the remaining traverse.

  Contact sensors are located on bumpers on the front and rear of the rover solar panel, and on the lower front body of the rover. Additional contact sensors are incorporated into the APXS deployment mechanism, which is located at the rear of the rover. If an obstacle in the rover’s path is not detected by the proximity hazard detection system, triggering any of the bumper contact sensors with either abort the traverse or cause the rover to back up, turn, and avoid the hazard.

  If a specified waypoint destination is not reached within the time allotted in the command, the command will time out, setting an error flag. This prevents the rover from continuing unproductive attempts to achieve an unreachable goal. Depending on the parameter settings in the sequence, any remaining traverse commands will be skipped (since the rover is not where it was expected to be), or the rover will continue on to the next specified location, which may be reachable.

- The “Find Rock” command allows the rover to zero in on a rock target at the end of a traverse, autonomously correcting for possible dead reckoning error. The usual strategy to reach a specific rock for APXS data collection is to first traverse to the vicinity of the target via one or more “Go to Waypoint” commands. Once there, the rover executes a “Turn Toward” the expected rock location, so that the rover is now facing in the direction the rock is most likely to be found. (The “Go to Waypoint” command does not specify the final heading of the rover at the end of a traverse.) The rover then executes a “Find Rock” command specifying coordinates beyond the rock’s actual position. The “Find Rock” executes in the same way as a “Go to Waypoint,” except that the first time a rock hazard is found during its traverse, the rover will stop, then turn in place while using its hazard detection sensors to determine the extent of the object, and finally turn to face the center of the rock.

- To provide full flexibility for rover control, low level motion commands are available. Additionally, hazard detection capabilities can be disabled if a specific circumstance so indicates.

Contingency Scenario Responses

- **Command Loss (Earth/Lander Link)**
  - Backup command sequence load stored on lander
  - Lander releases sequences to rover buffer in coordination with lander sequence execution
  - Rover executes sequences nominally, “unaware” of contingency situation
  - Approach allows for continued rover/lander activity coordination

- **Rover/Lander Communications Link Failure**
  - Rover transitions to contingency mission when a specified number of hours (nominally 48) has elapsed since last successful receipt of command sequence upload
  - Appropriate on-board contingency sequence triggered, depending on rover mission phase when contingency state began
  - Rover assumes lander is still listening, sends telemetry without requiring handshaking from lander
  - Any rover telemetry received by lander during rover contingency mission is sent to Earth as “unrecognized rover packets”
  - Rover continues to check for lander response, reverts to standard operation when command sequence successfully received from lander

Contingency Scenario Responses

- The Mars Pathfinder mission has prepared for the possibility of loss of communications with the spacecraft after landing. If the loss of communications is two-way then no mission is possible (or any results of such a mission would never be known). However, if only the receiver on the lander has failed, then telemetry from the spacecraft would still be received on the ground; only the opportunity to command the spacecraft (and rover) is lost. In order to perform a useful mission under such a “command loss” scenario, a Backup Mission Load (BML) is being designed to be uplinked to the spacecraft during the cruise mission phase. The BML includes a set of command sequences for both the lander and the rover. The BML will be activated after sufficient time (2 sols) has elapsed since the lander has received any sequences from the Earth. The lander will release sequences to the rover to stand up, deploy down the lander ramp, and perform surface operations. The lander will transmit telemetry, with the hope that it will be received by the DSN.

  Since, in this scenario, the rover will regularly receive new sequences, it will continue to operate in a nominal mode. The BML will allow some coordination of lander and rover activities during the early part of the mission. For the first few sols, until dead reckoning error accumulates to significant levels, the lander should be able to point its camera to image the rover at its end-of-day location. When BML sequences from the lander would no longer be useful (i.e., when the rover’s location is effectively unknown), the rover will be allowed to transition to its own onboard contingency sequence.

- If the communications link between the rover and lander fails, no coordination of activities will be feasible. When the rover receives no command sequence for approximately two sols, it will activate its contingency mission. The particular sequence to be triggered depends on the mission phase of the rover. If the rover is still on the lander petal, the sequence will cause it to stand up, then transition to the next phase for driving down the ramp. If the rover is already performing surface operations when the communications link fails, it will activate a sequence that continues surface operations, attempting to circumnavigate the lander, while finding rocks, taking APXS measurements, performing MAE, WAE, and soil experiments, and imaging. Each telemetry frame generated by the sequence will be transmitted twice. Without handshaking, the lander has no mechanism to determine into what kind of rover packet to reassemble the telemetry, so all telemetry would be classified as “unrecognized rover packets” and forwarded to the ground for reconstruction. If communications is reestablished, the rover resumes normal operation immediately when a command sequence is successfully received from lander. At appropriate intervals during the nominal surface mission, new contingency sequences will be uploaded to ensure that the most useful mission will be performed in the event of future communications loss.

Summary

Characteristics of the Mars Pathfinder Microrover

- **A simple spacecraft**
- **A serial machine - "Can't talk and chew gum at the same time"**
- **Operates in a non-deterministic environment - each step may yield unexpected results due to unknown terrain conditions**
- **Event driven**
  - many commands (e.g., waypoint traverse) have significant (although bounded) uncertainty in execution time
  - command execution start time is determined by time of completion of previous command
- **Probably the most autonomous deep space probe yet launched**
  - although modest in capability and complexity, the microrover is unique among robotic missions to date in its ability to operate in an unmodeled environment and choose actions based on sensor input to accomplish requested objectives